A cost-benefit analysis of the use of ammonia and hydrogen as marine fuels

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1. ABSTRACT:

A major challenge for the maritime industry during the last decades lies with its "obligation" to reduce the greenhouse gas (GHG) emissions from its operations and contribute to both global and regional targets for climate neutrality and decarbonization, like the Paris Agreement and the European Green Deal. In this direction, the "IMO Initial Strategy for the Reduction of GHG emissions from Shipping" calls for urgent action in order to reduce shipping GHG emissions by 50% by 2050 -when compared to 2008- and completely decarbonize the industry before the end of this century. The replacement of fossil fuels by alternative fuels and energy sources is absolutely necessary in this respect and a number of alternative fuels with GHG emission reduction potential have been proposed and considered for marine application. Among the different marine fuels, hydrogen and ammonia seem to have the higher environmental benefits and potential to achieve the decarbonization of maritime transport, but their adoption comes with high capital investments for the installation of new engines and fuel systems, port infrastructure, and increased operational costs due to their high prices compared with the conventional fuels. This paper analyses the costs and benefits associated with the use of hydrogen and ammonia as marine fuels focusing on various production methods, comprising blue fuels – produced from fossil sources and using carbon and capture storage (CCS) - and green fuels – coming from renewable energy sources. A cost-benefit analysis of the use of hydrogen and ammonia as marine fuels is essential in order to specify and underline the cost differences between these fuels and the conventional ones and make policy recommendations on how this existing 'cost gap' could be somehow alleviated through market-based measures (MBMs) to stimulate further investments on these fuels. Additional identified challenges associated with the use of these fuels – including availability, safety and regulatory aspects - are also touched upon in this paper.

Keywords: *shipping; decarbonization; alternative fuels; hydrogen; ammonia.*

2. INTRODUCTION

A major challenge for the maritime industry during the last decades lies with its "obligation" to reduce the greenhouse gas (GHG) emissions from its operations and contribute to both global and regional targets for climate neutrality and decarbonization, like the Paris Agreement and the European Green Deal. In this direction, the "IMO Initial Strategy for the Reduction of GHG emissions from Shipping" calls for urgent action in order to reduce shipping GHG emissions by 50% by 2050 -when compared to 2008- and completely decarbonize the industry by the end of this century (MEPC, 2018). The Initial IMO GHG Strategy incorporates a large variety of technical and operational measures for the improvement of the sector's energy efficiency. At the same time, it "suggests" the introduction of market-based measures (MBMs) in order to provide additional incentives for investments on green technologies and underlines the urgent need for the replacement of fossil fuels by alternative fuels and energy sources for the achievement of shipping decarbonization.

Besides the global regulations and initiatives for the decarbonization of the maritime industry, the European Green Deal and the most recent European Union's (EU) "Fit for 55" package include specific legislations that target the drastic reduction of GHG emissions from shipping at European level recognizing the crucial contribution of shipping in the overall efforts for the achievement of climate neutrality in Europe by 2050 and the reduction of the relevant emissions by 55% by 2030 (Council of the European Union, 2021). A number of legislation tools within the EU's "Fit for 55" package seek to improve the energy efficiency and carbon footprint of shipping with the most 'mature' being the inclusion of shipping in the EU Emissions Trading System (EU ETS) that is planned to enter into force in 2024. Another important regulation that aims to significantly increase the employment of alternative marine fuels and energy sources is the FuelEU Maritime Initiative that "sets specific GHG intensity limits on the energy used on-board ships" and is planned to enter into force in 2025. More specifically, the FuelEU Initiative requires all vessels operating within the EEA, departing or arriving from/to an EU port to meet specific GHG intensity limits that will gradually become stricter – starting from 2025 to 2050 – with the GHG reductions required in 2050 reaching 75% of the energy used in 2020 that is baseline year for the implementation of the Initiative (Christodoulou and Cullinane, 2022).

In this respect, a number of alternative fuels with GHG emission reduction potential have been proposed and considered for marine application (Bouman et al., 2017; Wan et al., 2018; Foretich et al., 2021). Among the different marine fuels, hydrogen and ammonia seem to have the higher environmental benefits and potential to achieve the decarbonization of maritime transport, but their adoption comes with high capital investments for the installation of new engines and fuel systems, port infrastructure, and increased operational costs due to their high prices compared with the conventional fuels (McKinlay et al., 2021; Wang et al., 2021; Masodzadeh et al., 2022). Additional barriers for the wide adoption of hydrogen and ammonia as marine fuels are the safety considerations associated with their use, the existing regulatory framework that does not include them as "certified" marine fuels and their current limited availability that cannot meet the energy needs of the global fleet (Ampah et al., 2021).

This paper analyses the costs and benefits associated with the use of hydrogen and ammonia as marine fuels focusing on various production methods, comprising blue fuels – produced from fossil sources and using carbon and capture storage (CCS) - and green fuels – coming from renewable energy sources. A cost-benefit analysis of the use of hydrogen and ammonia as marine fuels is essential in order to specify and underline the cost differences between these fuels and the conventional ones and make policy recommendations on how this existing "cost gap" could somehow be alleviated through market-based measures (MBMs) to stimulate further investments in these fuels. Additional identified challenges associated with the use of these fuels – including availability, safety and regulatory aspects - are also touched upon in this paper.

The paper is organized as follows: A short introduction on blue/green hydrogen and ammonia as marine fuels is provided in Section 3 followed by Section 4 that presents the method and data used in this analysis. The results from the cost-benefit analysis of the use of these alternative marine fuels are analysed and discussed in Section 5. Section 6 presents the main conclusions and policy recommendations of this research.

3. GREEN AND BLUE HYDROGEN AND AMMONIA

Both hydrogen and ammonia can be employed as marine fuels in different forms based on the energy sources used for their production. In case their production is based on fossil energy sources, they can be grey or blue hydrogen or ammonia; in case they are produced from renewable energy, they are called green or e-fuels. Blue hydrogen and ammonia – in contrast to grey fuels – use carbon capture and storage (CCS) technology during the fuel production in order to reduce their carbon intensity, a reduction that reaches up to 90% compared to grey fuels. Besides their low carbon intensity from the use of CCS, blue hydrogen and ammonia cannot be considered as fossil-free fuels in contrast to green hydrogen and ammonia that are produced from electricity coming from renewable energy sources such as solar, wind, hydro, tidal wave, and geothermal energy. At the moment, the vast majority of hydrogen produced (95%) comes from fossil fuels, while only 5% being green hydrogen produced through electrolysis.

The carbon intensity of grey hydrogen is higher than heavy fuel oil (HFO) and marine gas oil (MGO); GHG emissions reductions from the use of green hydrogen are, though, even higher than 85% of conventional fuels. Green hydrogen is a sulfur free fuel with very low carbon intensity that could be used for the energy transition of maritime transport. There are, though, some characteristics of the fuel that make it less attractive compared to other options. A practical disadvantage of using hydrogen as marine fuel comes from its low energy density that requires high fuel storage volumes onboard and reduces the cargo space on the concerned vessels. Its volumetric energy density is low (5.14 GJ/m³) when stored in compressed state at 80 MPa pressure, and slightly higher (8.55 GJ/m³) when stored as liquid at cryogenic conditions (-253°C) (Lemmon et al., 2010). It is exactly this low volumetric energy density of hydrogen that makes weak its business case for use in deep-sea shipping where the needed fuel storage volumes are very higher compared to conventional fuels. Additionally, hydrogen is easily ignitable over a wide range of fuel-air mixing ratios and has a Global Warming Potential over 100 years estimated to be between as high as 11 (Sand et al., 2020). These conditions turn safe storage and handling of hydrogen onboard the vessels into major challenges for the employment of hydrogen as marine fuel with the need to pay particular attention to safety considerations.

The demand for hydrogen as marine fuel is still emerging at the moment, with no distribution or bunkering infrastructure for ships currently in place. There are, though, upcoming port initiatives on the building of refueling points for hydrogen at major ports around the globe, with the Port of Rotterdam standing out. The unique areas where ports are located also turn them into promising energy hubs for the production and storage of renewable energy that could also be used for the production of green fuels.

Coming to the employment of ammonia as marine fuel, the GHG footprint of this fuel depends on the energy sources used for its production. As in the case of hydrogen, grey ammonia usually comes from natural gas or coal and has a carbon footprint close to fossil fuels; green ammonia, though, that comes from renewable electricity, water and air can lead to almost zero CO_2 emissions while blue ammonia that comes from fossil sources, but uses CCS during its production can also drastically reduce CO2 emissions (Hansson et al., 2020). However, the high toxicity of ammonia and safety considerations that come with its handling as a marine fuel need to be addressed (Prussi et al., 2021).

Compared to hydrogen, ammonia is easier and less energy consuming to store requiring less severe temperature and pressure conditions for its transportation. More specifically, the conditions at which ammonia becomes liquid are either (-33°C) at atmospheric pressure, or 15 bar at atmospheric temperature (25°C) (Lemmon et al., 2010), which are well below the ones required for hydrogen storage onboard. Moreover, ammonia is already transferred as a cargo by sea with 120 ports across the globe already having in place facilities for handling ammonia. Yet, the toxicity and volatility of ammonia remains an important albeit manageable challenge (Schönborn & Lee, 2022). The bunkering infrastructure for ammonia is not yet in place in any port around the world; this consists one of the main challenges for its wider adoption as a marine fuel along with the limited availability of ammonia, and especially green ammonia. It is also necessary to factor in that the production of green ammonia is currently emerging (77% of ammonia produced globally is grey, the high investment costs associated the land-based infrastructure are an additional challenge for its wider adoption as a marine fuel (Krantz et al., 2020).

4. METHOD/DATA

After this short introduction to green/blue ammonia as marine fuels and their potential to fully decarbonize the maritime sector, this paper analyses the costs and benefits associated with the use of these fuels. A cost-benefit analysis of the use of hydrogen and ammonia as marine fuels is essential in order to specify and underline the cost differences between these fuels and the conventional ones and make policy recommendations on how this existing 'cost gap' could be somehow alleviated through market-based measures (MBMs) to stimulate further investments on these fuels.

In order to estimate the costs associated with the employment of hydrogen and ammonia as marine fuels, the cumulative cost for the lifespan of a ship is calculated using the function below considering both the capital expenditure (CAPEX) and the operational expenditure (OPEX) (Kim et al., 2020). The CAPEX includes the investment cost in €/kW for the propulsion systems, including engines and components (for four-stroke and two-stroke engines) (Korberg et al., 2021), while the fuel costs are included in the OPEX.

(1) $$\text{Cumulative cost} = CAPEX + \sum_{n=1}^{n=25} \frac{OPEX*(1+i)^n}{(1+d)^n}$$

where n is the age of the ship from 1 to 25 years, d is the discount rate and r is the inflation rate.

Based on Korberg et al. (2021), the investment cost in €/kW for the different propulsion systems, including engines and components (for four-stroke and two-stroke engines) can be found in Table 1 along with the cost of the SCR (45€/kW). The fuel prices for MDO, NH3 and H2 are also shown in Table 2 and are based on Inal et al. (2022).

Table 1. Investment cost in €/kW for the different propulsion systems, including engines and components (for four-stroke and two-stroke engines)

Engine type	Fuel	Engine cost/kW
4-stroke (4S)	MDO	240
	NH3	370
	H2	470

2-stroke (2S)	MDO	460
	NH3	600

Table 2. Fuel prices in €/tonne of fuel for MDO, NH3 and H2 (Inal et al., 2022)

Fuel	Fuel price	2036-2050
MDO	550	
Blue NH3	375	
Green NH3	750	360
Blue H2	2200	
Green H2	5500	2600

It needs to be mentioned here that the fuel prices for green hydrogen and ammonia for the period

2036-2050 are based on the authors' assumptions that the increased demand for these fuels and the technology maturity for their production will lead to reduced prices over the years.

In order to estimate the benefits from the employment of blue/green hydrogen and ammonia as marine fuels, the emission costs from the use of the different marine fuels were calculated by multiplying the life-cycle emissions from the use of each fuel with the fuel consumption of the vessel and the emission costs per tonne of emission using the formula below:

(2)

Cm,m´,bn,gn,bn´,gn´,bh,gh = Ec,s,n,p * C´c,s,n,p

where Cm,m´,bn,gn,bn´,gn´,bh,gh are the emission costs from the use of the MDO in 4stroke engines, MDO in 2stroke engines, blue and green NH3 in 4stroke engines, blue and green NH3 in 2stroke engines and blue and green H2 in 4stroke engines. Ec,s,n,p are the life-cycle CO2 eq., SOx, NOx, PM emissions per kWh from the use of the different fuels. C´c,s,n,p are the emission costs per tonne of CO2 eq., SOx, NOx, PM emissions (Victoria Transport Policy Institute, 2020). The emission costs per tonne of pollutant that were assumed in this study are: 90€/tonne of CO2eq., 6500€/tonne of SOx, 4700€/tonne of NOx and 2500€/tonne of PM2,5.

Following the analysis of the emission costs associated with the employment of each fuel, their environmental performance was revealed along with the benefits from their employment. Besides the cost-benefit analysis, we further attempted to incorporate the identified external cost (emission cost) to the production cost in order to underline the actual social cost of each fuel.

5. RESULTS AND DISCUSSION

The first part of this section presents our findings on the costs associated with the use of hydrogen and ammonia as marine fuels, while the second part focuses on the benefits from their employment.

5.1 CAPEX and OPEX for the use of MDO, NH3 and H2 as marine fuels in 4stroke and 2stroke engines

In this study, we analysed the case of a tanker vessel with an engine of 6000 kW, a discount rate of 2% and an inflation rate of 10%. The CAPEX for this vessel for the use of the various fuels will be calculated using the following formula:

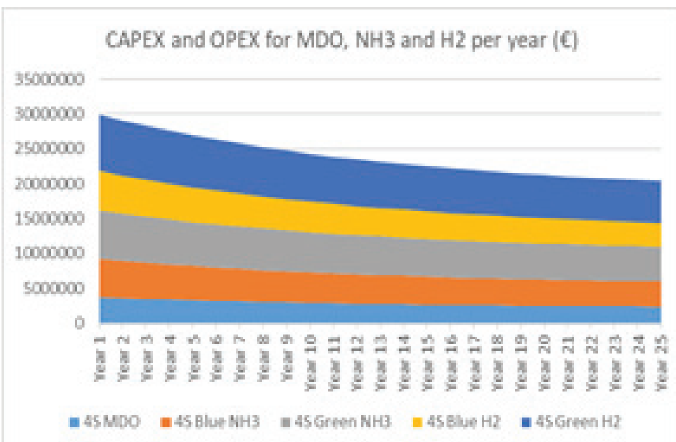
(3)

CAPEX = (engine cost/kW + SCR cost/kW) * KW

The OPEX will be calculated by multiplying the fuel prices with the fuel consumption of each fuel that depends directly on the energy density of the different fuels. Based on the existing literature, the energy density of MDO is 42.6 MJ/kg, of NH3 18.6 MJ/kg and of H2 MJ/kg 120.0 (Dong et al., 2023). It needs to be mentioned here that different scenarios have been considered for the use of each fuel. For MDO, the use of the fuel is 100% at both 4stroke and 2stroke engines, for NH3 the use of 88% of this fuel (and 12% of MDO) is considered for 4stroke engines with these percentages being 95% of NH3 (main fuel injection) and 5% of MDO (pilot fuel injection) for 2stroke engines, for H2 the use of

98.5% (main fuel injection) of this fuel is considered with 1.5% (pilot fuel injection) of MDO for 4stroke engines (Dong et al., 2023).

Following the formula used for the calculation of the CAPEX and OPEX, the yearly CAPEX and OPEX of the tanker for the use of the different fuels can be seen in the following figure 1.



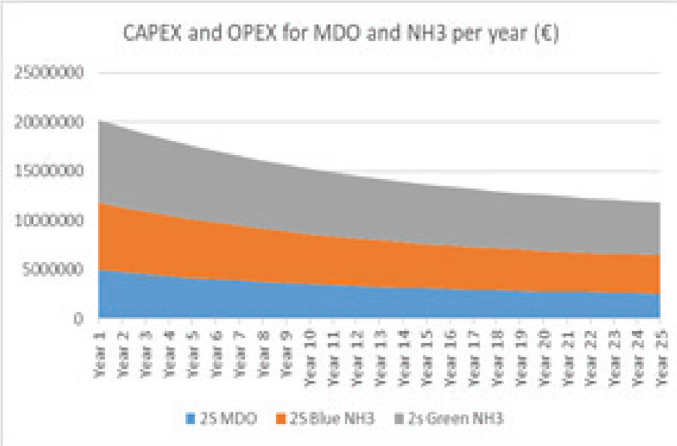


Figure 1: CAPEX and OPEX for different fuels per year (€)

As can be seen in Figure 1, green hydrogen and ammonia are by far the most expensive fuels with their annual cost decreasing over the years, but still remaining much higher than the cost of MDO and blue hydrogen and ammonia. The main reason lies to the high OPEX of green fuels as their price is very high at the moment due to their limited availability and technological maturity for their production. In contrast to conventional fossil fuels, the employment of hydrogen and ammonia imply additional CAPEX coming from the conversion of existing marine engines (Hansson et al., 2020; Lindstad et al., 2021).

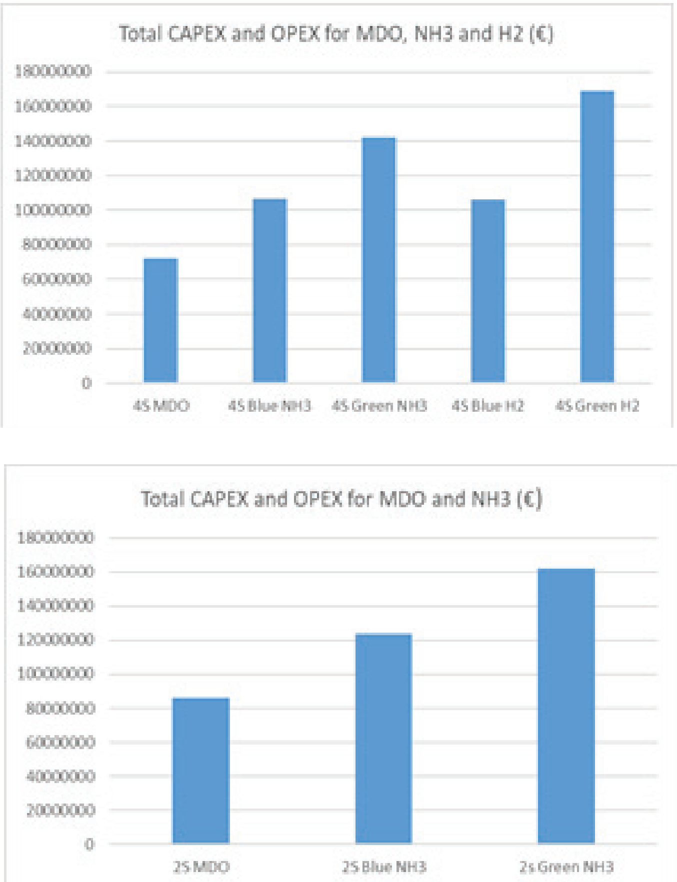


Figure 2: CAPEX and OPEX for different fuels for the whole lifespan of the vessel (€)

Figure 2 presents the CAPEX and OPEX for different fuels for the whole lifespan of the vessel and makes apparent the "cost gap" between the conventional MDO and blue/green hydrogen and ammonia. The overall cost of using green hydrogen (4S engines) reaches almost 170 million euros for the whole lifespan of the vessel, while blue hydrogen costs around 106 million euros compared to MDO that costs around 72 million euros. When green ammonia is used in 4S engines, the fuel costs are double the costs of MDO (142 million euros) and go down to 107 million euros when blue ammonia is used.

5.2 Emission costs from the use of different marine fuels

Shifting the discussion towards the emission costs from the use of the different marine fuels, these were calculated by multiplying the life-cycle emissions from the use of each fuel with the fuel consumption of the vessel and the emission costs per tonne of emission using the formula below:

$$C_{m,m',bn,gn,bn',gn',bh,gh} = E_{c,s,n,p} * C'_{c,s,n,p} \quad (4)$$

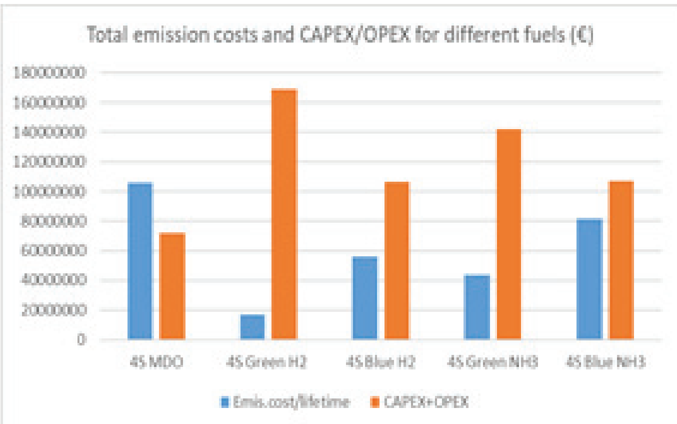
where $C_{m,m',bn,gn,bn',gn',bh,gh}$ are the emission costs from the use of the MDO in 4stroke engines, MDO in 2stroke engines, blue and green NH4 in 4stroke engines, blue and green NH3 in 2stroke engines and blue and green H2 in 4stroke engines. It needs to be mentioned here that different scenarios have been considered for the use of each fuel. For MDO, the use of the fuel is 100% at both 4stroke and 2stroke engines, for NH3 the use of 88% of this fuel (and 12% of MDO) is considered for 4stroke engines with this percentages being 95% of NH3 and 5% of MDO for 2stroke engines, for H2 the use of 98.5% of this fuel is considered with 1.5% of MDO for 4stroke engines. $E_{c,s,n,p}$ are the life-cycle CO2 eq., SOx, NOx, PM emissions per kWh from the use of the different fuels. $C'_{c,s,n,p}$ are the emission costs per tonne of CO2 eq., SOx, NOx, PM emissions (Victoria Transport Policy Institute, 2020).

The life-cycle emissions of different fuels include Well-to-Wake GHG emissions of alternative fuels considering both Well-to-Tank emissions generated during the production, process, transport of fuel to the ship and bunkering and Tank-to-Wake emissions produced from the combustion of marine fuels. Based on existing literature, the Well-to-Wake GHG emissions of green ammonia and hydrogen are very low compared to conventional fuels and they have the potential to decarbonize shipping, but – as seen in the previous section – their employment presupposes high operational and capital expenditure and investments in new infrastructure (Hansson et al., 2020; Lindstad et al., 2021). Dong et al. (2023) calculated the life-cycle CO2 eq., SOx, NOx, PM emissions per kWh of MDO, ammonia and hydrogen considering the same scenarios used in this cost-benefit analysis (Table 3).

Table 3. Life-cycle CO2 equiv., SOx, NOx, PM emissions per kWh from the use of the different fuels (Dong et al., 2023)

Scenarios	CO2 equiv.	SOX	NOX	PM
100%MDO+SCR 2-stroke	6.64E-01	2.47E-04	1.24E-03	3.30E-04
95%GreenN-H3+5%MDO+ SCR 2-stroke	1.14E-01	1.23E-05	1.02E-03	3.22E-05
95%BlueN-H3+5%MDO+ SCR 2-stroke	4.18E-01	1.23E-05	1.45E-03	3.71E-05
100%MDO+SCR 4-stroke	8.08E-01	3.01E-04	1.51E-03	4.02E-04
98.5%Green-H2+1.5%MDO 4stroke	5.03E-02	4.67E-06	2.11E-03	1.47E-05
98.5%Blue-H2+1.5%MDO 4stroke	3.97E-01	4.67E-06	2.60E-03	2.02E-05
88%GreenN-H3+12%MDO +SCR 4-stroke	3.10E-01	8.88E-05	1.49E-03	1.08E-04
88%BlueN-H3+12%MDO +SCR 4-stroke	6.45E-01	1.26E-04	2.00E-03	1.00E-04

Turning the focus to the emission costs per tonne of CO2 eq., SOx, NOx, PM emissions, average costs have been calculated based on Victoria Transport Policy Institute (2020) (Victoria Transport Policy Institute, 2020). The emission costs per tonne of pollutant that we assumed in this study is 90€/tonne of CO2eq., 6500€/tonne of SOx, 4700€/tonne of NOx and 2500€/tonne of PM2,5. The total emissions costs from the use of each fuel throughout the lifespan of the vessel can be seen in the following figure along with the CAPEX and OPEX for the respective period.



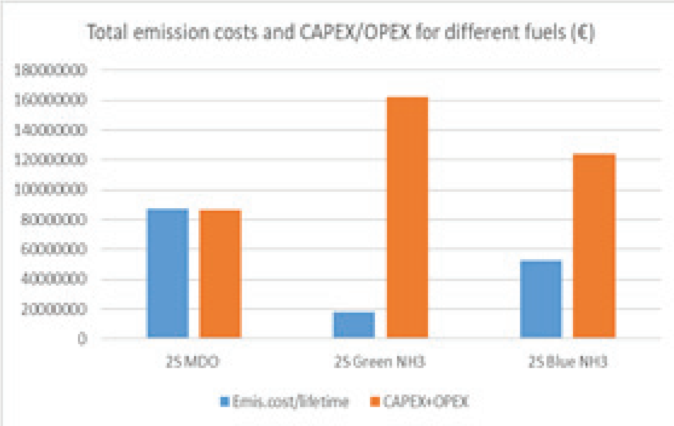
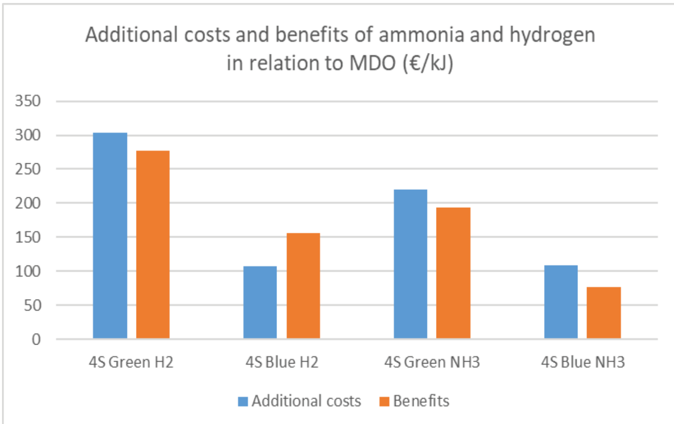


Figure 3: Total emission costs and CAPEX/OPEX for different fuels (€)

As can be seen in figure 3, for 4S engines the use of green hydrogen leads to the minimal emissions cost (external cost) compared to all other options accounting for 17 million euros, but is, at the same time, the most costly option with the total expenditure from its use reaching 170 million euros. Green ammonia represents the second best option in terms of external costs (44 million euros), but its use also leads to high CAPEX and OPEX (142 million euros) compared to conventional fuels. Following green hydrogen and ammonia, blue hydrogen comes third in terms of emissions cost (56 million euros) while blue ammonia comes fourth with an external cost of 81 million euros. Finally, as expected, the use of MDO generates a high external cost of 106 million euros and a low total expenditure of 72 million euros. The additional costs and benefits per kilojoule (kJ) from the use of hydrogen and ammonia as marine fuels throughout the lifespan of the vessel can be seen more clearly in figure 4.



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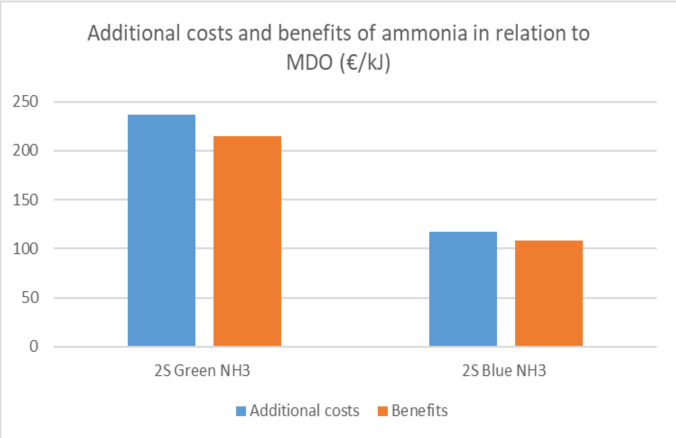

Figure 4: Additional costs and benefits of ammonia and hydrogen in relation to MDO (€/kJ)

The potential of ammonia and hydrogen to decarbonize shipping becomes quite obvious from the analysis undertaken in this research. Their life-cycle GHG emissions are far less than the ones generated from the use of MDO with the relevant external cost from their use also being minimal in comparison to conventional options. Besides their environmental benefits, though, the high total expenditure for their employment also becomes apparent underlining the urgent need to provide additional incentives to the industry in order to proceed with the necessary investments for the employment of alternative fuels and accelerate the energy transition of the sector. The introduction of market-based measures (MBMs) in the form of a global levy on marine fuel or an emissions trading system can internalize the external costs of conventional fuels and stimulate the employment of cleaner fuels by applying 'the polluter pays' principle (Wang et al., 2021; Christodoulou et al., 2021; Pomaska & Acciaro, 2022).

6. CONCLUSIONS AND POLICY IMPLICATIONS

This paper attempts to provide an assessment of the costs and benefits associated with the use of hydrogen and ammonia as marine fuels through a cost-benefit analysis in order to specify and underline the cost differences between these fuels and the conventional ones - especially MDO - and make policy recommendations on how this existing "cost gap" could be somehow alleviated through market-based measures (MBMs) to stimulate further investments on these fuels. Beginning with the cost assessment of the fuels, our analysis verifies the findings of existing literature that green hydrogen is by far the most costly option as marine fuel followed by green ammonia, blue hydrogen and blue ammonia. At the same time, though, the emission costs of green hydrogen (followed by green ammonia) are minimal compared to conventional – and even blue – fuels. Clearly, the use of renewable energy sources for the production of both hydrogen and ammonia is critical in order to achieve the decarbonization of shipping in the future.

The high total expenditure associated with the use of green fuels turns the introduction of MBMs - carbon taxes on marine fuels based on their GHG energy intensity or through the subsidization of renewable fuels, at least in the initial phase of their uptake - essential in order to alleviate the "cost gap" between these fuels and the conventional ones and accelerate the employment of cleaner fuels. Although the production costs of green hydrogen and ammonia are expected to decrease in the long run due to technical maturity and increased demand, for the time being their high CAPEX and OPEX in comparison with the cost of MDO represent the greatest challenge for their wide adoption by the industry.

Apart from the economic factors, additional challenges associated with the use of these fuels need to be addressed; indicative examples encompass safety concerns, regulatory aspects, restricted availability and an uncertain regulatory framework as different alternative fuels with GHG emission reduction potential have been proposed and considered for marine application. Safety concerns are quite often raised for the use of both ammonia and hydrogen for marine application due to their particular properties, the high explosivity of hydrogen and the corrosion and toxicity of ammonia. In this direction, the employment of ammonia and hydrogen as marine fuels is not allowed under the current IMO regulations and the relevant safety protocols need to be revised accordingly in order to proceed with the use of these renewable fuels. It should be mentioned here that not all renewable fuels are considered suitable for use for all maritime segments. Especially with regards to short sea shipping, electrification is gaining momentum for the decarbonization of short distances while the use of ammonia for passenger transport is not considered as a feasible option given the safety concerns associated with its employment as marine fuel.

At the moment, the production of renewable fuels is limited and the refueling infrastructure at ports for their employment is currently being developed with major ports around the globe building refueling facilities for the supply of several alternative fuels. Besides the IMO regulations and port initiatives, a number of shipping companies around the globe have already invested in alternative fuels ordering newbuildings with dual engines that can use both conventional fuel and ammonia (Christodoulou and Cullinane, 2021). Shipping industry coalitions can also play a critical role for scaling up the uptake of renewable fuels and accelerating the energy transition of the sector. Green corridors – an industry-driven initiative that seeks to create "specific trade routes between major port hubs where zero-emission solutions have been demonstrated and are supported" – can pave the way for the development of ecosystems 'with targeted regulatory measures, financial incentives, and safety regulations that can also put conditions in place to mobilise demand for green shipping on specific routes' (Getting to Zero Coalition, 2020).

7. ACKNOWLEDGMENTS

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